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An Assessment of the Potential for Neck Injury Due to Padding of Aircraft Interior Walls for Head Impact Protection

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16. Abstract <p>This report describes a short test program to assess the potential for neck injury induced by placing padding on the interior walls of an aircraft cabin to reduce the possibility of a head injury during a crash. Such padding is a possible mechanism of achieving the heightened impact protection requirements adopted by the Federal Aviation Administration in 1988. The report reviews the literature on impact induced neck injury, and reports neck injury criteria developed and reported by others. The type of test device to use with the neck injury criteria is also discussed. Using the reported neck injury criteria, and a Hybrid III test dummy with neck instrumentation, the testing program found that neck injury, with one exception, was not likely in either the tested pad or unpadded case. The one exception was neck extension injuries for which both the unpadded and padded tests exceeded the injury criteria. The tested pad, in comparison to the unpadded case, substantially decreased the neck extension moment, implying a reduction in neck injury risk.</p>			
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AN ASSESSMENT OF THE POTENTIAL FOR NECK INJURY DUE TO PADDING OF AIRCRAFT INTERIOR WALLS FOR HEAD IMPACT PROTECTION

INTRODUCTION

Head injuries are some of the most frequent types of serious injury and causes of death found in airplane accidents. In 1988, the Federal Aviation Administration (FAA) adopted amendments to the Federal Aviation Regulations (FARs), which require seats to meet specific crashworthiness performance criteria. Included in the new regulations is the demonstration of head injury protection by means of dynamic impact sled tests using anthropomorphic test devices (ATD), commonly known as crash dummies. While the evaluation of neck injury is not required by the FARs, it is important that techniques developed to reduce the severity of head impact do not induce injurious reactions in the neck.

The use of padding has been shown to be effective in reducing the potential for a head impact injury. However, a common concern in designing a pad to reduce the threat of a head injury is that the pad may create new load paths which create a potential for a neck injury. The test program described in this report sought to determine the threat of a neck injury associated with a padding material effective in reducing the potential for head injury. In addition to describing the results of the test program, this report also describes techniques and injury threshold values to use in assessing the potential for an impact injury to the neck.

BACKGROUND

Although the focus of concern in this study is head and neck injury as it relates to aviation safety, the majority of information on head and neck injury has come from automotive safety research. Since it is unacceptable to study impact tolerance directly using living human subjects, several methods of study have been employed to gain information about head and neck injury biomechanics.

One of the earliest methods was aircraft and automotive accident investigation. Data from these studies are limited because measurements cannot be made during the impact (Viano, et al., 1989). Animal models have been used to gain insight into the physiologic responses of living tissue (NHTSA, 1981). Although this information is useful on a cellular level, reliable data on the biomechanical mechanism of injury are limited because of the potential errors in scaling to human values. In addition, the physiological effect of the anesthesia used with these animals is unknown (Viano, et al., 1989; Demann, et al., 1990). Some human volunteer studies, generally using healthy young males, have been performed at impact severity levels below the pain threshold. Human cadaveric test subjects have been utilized to simulate gross geometric, inertial, and joint range-of-motion properties, but little information can be inferred about physiologic response (Viano, et al., 1989). Attempts to directly measure the forces acting on the body during an impact have been done through the use of ATDs. The newest of these test dummies, the Hybrid III, is used in this study.

The neck of the Hybrid III dummy was designed to approximate the dynamic response of the human neck (Foster, et al., 1977). Although the Hybrid III does not exactly match human neck dynamics, it is the best model available at this time for human biomechanical measurements of the neck (Viano, et al., 1987).

REVIEW OF INJURY MECHANISMS AND INJURY CRITERIA

Head injury mechanisms have been extensively studied. Generally accepted mechanisms of head injury include: (1) brain contusion due to skull deformation; (2) brain contusion from movement of the brain against irregular interior cranial surfaces; and (3) stress and strain in neural tissues caused by pressure gradients and motion relative to the skull or dural envelope, resulting in brain and spinal cord injury and tears of blood vessels (Viano, et al., 1989; Demann, 1990).

Several head injury criteria have been developed. HIC (Head Injury Criterion) as defined in Department of Transportation regulations (e.g., Title 14, Code of Federal Regulations, Parts 23, 25, 27, or 29, or in Federal Motor Vehicle Safety Standard 208) is the most widely used. HIC is based on research performed in the 1950's and 1960's at Wayne State University which resulted in the Wayne State Tolerance Curve (WSTC) (Lissner, et al., 1960, 1961). The WSTC relates a combination of acceleration magnitude and time duration to a head injury. HIC is a functional relationship combining time and acceleration magnitude. HIC is defined by the following equation:

$$HIC = (t_2 - t_1) \left[\int_{t_1}^{t_2} a(t) dt \right]^{2.5}$$

where:

$a(t)$ = acceleration as a function of time of the head center-of-gravity

t_1, t_2 = time limits of integration that maximize HIC

HIC values greater than 1000 indicate that a serious head injury is likely. As HIC increases, the likelihood and severity of head injury increases. A HIC equal to 1000 is believed to represent a 16% probability of a life threatening brain injury (Prasad and Mertz, 1985; Viano, et al., 1989). HIC suggests that a higher acceleration for a shorter period of time is less injurious than a lower level of acceleration for a longer period of time.

The literature on cervical spine injury is not as well developed as that of head injury. Impact to the head may result in neck flexion, extension, lateral flexion, rotation, compression, tension, or a combination of these motions.

An accident causing tension-flexion at the neck can result in atlanto-occipital (A-O) and C1-C2 separations (Melvin, et al., 1986). Compression-flexion injuries are generally a result of a force to the posterior-superior head. Anterior wedge fractures, burst fractures, and fracture dislocations of facets can occur leading to instability and cord injury (Melvin, et al., 1986; McElhaney, et al., 1976). The tension-extension mechanism primarily produces

whiplash type injuries, but fractures of the anterior vertebral body, separation of the anterior disk from the vertebral end plate, and hangman's fracture can occur (McElhaney, et al., 1976; Melvin, et al., 1986). During an impact producing a compression-extension load on the neck, fractures of spinous processes and lesions of the pedicles, facets, and laminae causing dislocation can occur. A frontal (forehead) impact frequently produces these injuries (Melvin, et al., 1986). Lateral flexion of the neck may cause lateral wedge or lateral posterior element fractures on one side (Melvin, et al., 1986). Dens fractures occur when the head in a neutral position impacts, but the body continues forward causing a shearing force between the atlas and dens. A second mechanism for dens fracture is acute flexion of the head while the cervical spine is extended (McElhaney, et al., 1976).

Injury tolerances of the cervical spine have been examined in terms of the loads applied to the neck and measured at the occipital condyles. Tolerance levels for neck flexion and extension have come from tests of human cadaveric subjects, and human volunteers (Mertz and Patrick, 1967, 1971; Melvin, et al., 1986; McElhaney, 1976). Tolerance levels for lateral flexion have come from human volunteer tests only (Patrick and Chou, 1976; Melvin, et al., 1986; McElhaney, 1976).

In 1982 the Biomechanics Division of the National Highway Traffic Safety Administration (NHTSA) developed a series of relationships between impact injury severity and measurable parameters from an ATD (Eppinger, 1982). Injury severity was described in terms of the 1980 AIS (Abbreviated Injury Scale). AIS (American Association for Automotive Medicine, 1980) rates injury severity on a numeric scale from 0 to 6, with 0 being uninjured, and 6 representing immediate death (i.e., currently untreatable). AIS was revised in 1985 and 1990 but remains similar to the 1980 version. The relationships that Eppinger developed relate published injury criteria and the 1980 version of AIS. The neck injury criteria that Eppinger used were based on the work of Mertz, et al. (1967, 1971, 1978, 1984). A summary of the neck injury tolerance relationships that Eppinger presented in 1982 follow.

Some of the injury severities listed in the following relationships do not span the full range of the AIS values. This indicates that no tolerance data are available for higher AIS values. When low and high AIS values are listed, but no intermediate AIS values are shown, this demonstrates that neck injury is not a graded phenomenon. Neck injuries tend to be "minor" (e.g., whiplash) or catastrophic (e.g., cord separation). Often the difference in the load between a minor injury and a catastrophic injury is small.

The first injury relationships presented relate neck extension and flexion injuries to moments measured at the atlanto-occipital condyles in a human, and at the head-neck junction in the ATD. The Hybrid III has load cells mounted at the head-neck junction. The flexion and extension criteria are based on the work of Mertz, et al. (1971, 1973).

EXTENSION		FLEXION	
AIS	Moment (M)	AIS	Moment (M)
1	$M > 35 \text{ ft-lb}$	1	$M \leq 45 \text{ ft-lb}$
2	$M > 45 \text{ ft-lb}$	2	$M \leq 140 \text{ ft-lb}$
		5	$M \leq 150 \text{ ft-lb}$
		6	$M > 150 \text{ ft-lb}$

The lateral flexion criterion is based on the work of Patrick and Chou (1976). Patrick and Chou did not relate their injury tolerance curve to an injury severity level, and Eppinger did not consider lateral flexion injuries. Thus, the 29.5 ft-lb criteria is based on the onset of discomfort in human volunteers, and should be considered a level at which serious injury is unlikely.

LATERAL FLEXION

Moment(M)

$M \leq 29.5 \text{ ft-lb}$

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Interest in neck axial compression tolerance began following several severe injuries to football players. Axial neck loads were measured using a Hybrid III ATD to simulate football tackles that had resulted in serious neck injury to the actual football player. Based on these tests, a tolerance curve relating time and neck axial compressive force to injury was developed by Mertz, et al. (Mertz, et al., 1978, 1984; Eppinger, 1982; Melvin, et al., 1986). Mertz' curve is shown in Figure 1. The following criteria reflect this curve.

AXIAL COMPRESSION

AIS	Force (F in lbs)	Load Duration (t)
5	$F \geq 850 \cdot (t \times 20)$ $F \geq 250$	$t \leq 30 \text{ ms}$ $t > 30 \text{ ms}$
0	Otherwise	

Injury assessment criteria curves for axial tension and anterior-posterior shear force have been postulated based on Hybrid III studies (Mertz, 1984; Eppinger, 1982; NHTSA, 1981). The following guidelines are based on these curves, which are shown in Figures 2 and 3.

AXIAL TENSION

AIS	Force (F in lbs)	Load Duration (t)
5	$F \geq 250$ $F \geq 1680 \cdot (t \times 31)$ $F \geq 740 \cdot (t \times 2)$	$t \geq 45 \text{ ms}$ $45 > t \geq 34 \text{ ms}$ $t < 34 \text{ ms}$
0	Otherwise	

ANTERIOR-POSTERIOR SHEAR

AIS	Force (F in lbs)	Load Duration (t)
5	$F \geq 250$ $F \geq 760 \cdot (t \times 11)$ $F \geq 340$ $F \geq 700 \cdot (t \times 15)$	$t \geq 45 \text{ ms}$ $37 \text{ ms} \leq t < 45 \text{ ms}$ $25 \text{ ms} \leq t < 37 \text{ ms}$ $t < 25 \text{ ms}$
0	Otherwise	

Figure 1 - Injury criterion for neck axial compressive loading (Mertz, et al., 1978)

Note - Loads are in Newtons.

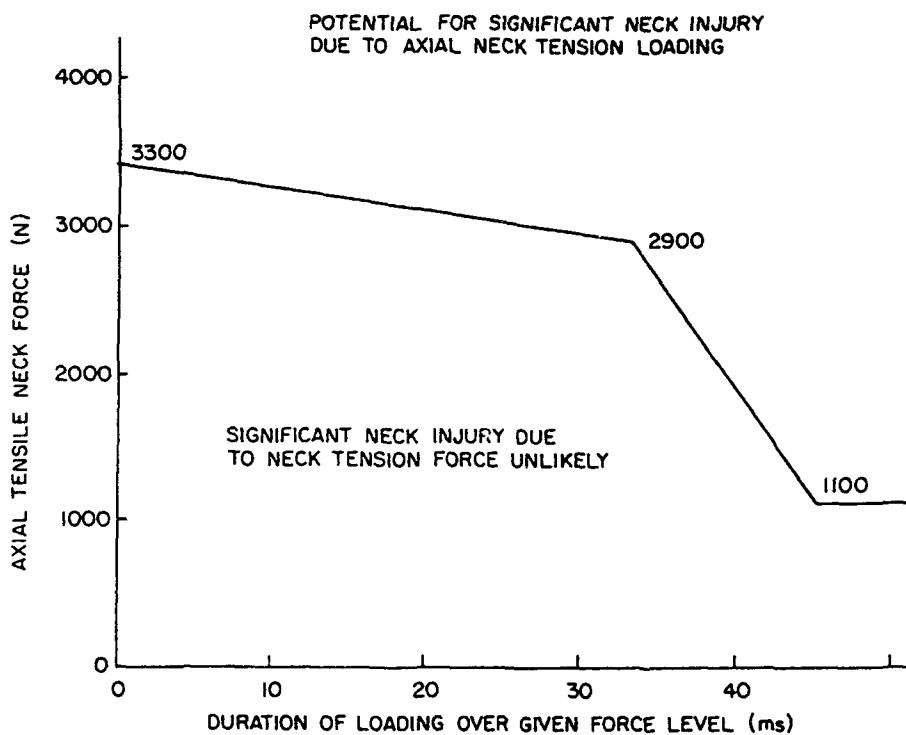
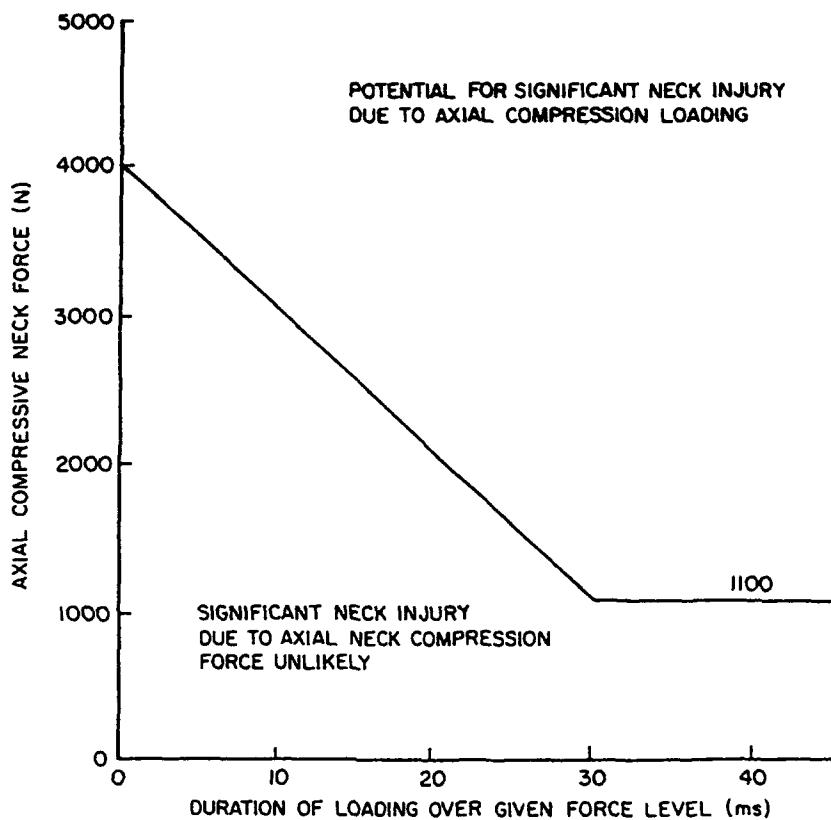


Figure 2 - Injury criterion for neck axial tension loading (Mertz, 1984)

Note — Loads are in Newtons.

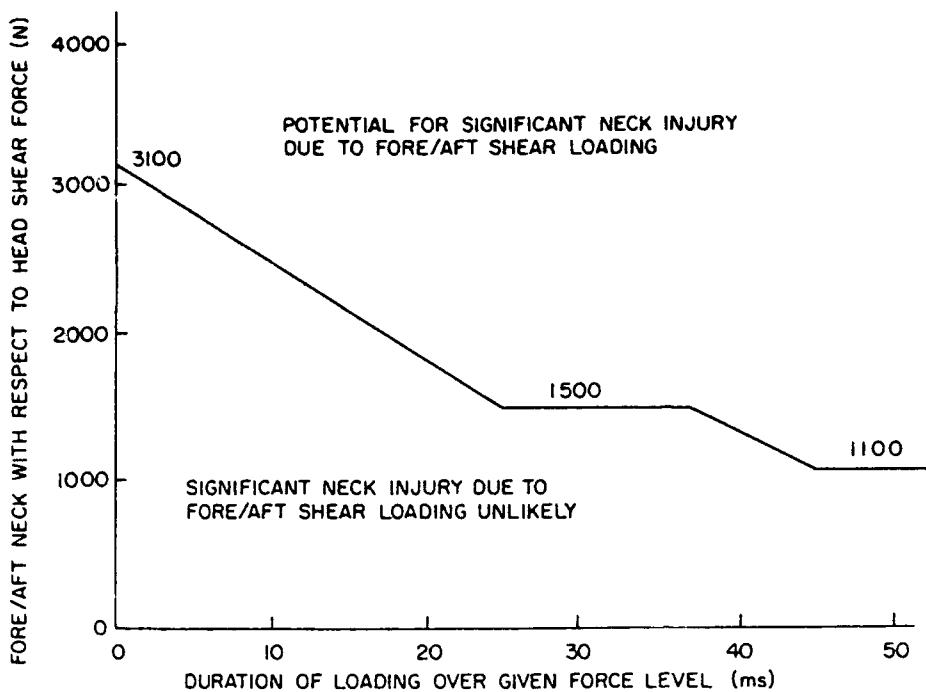


Figure 3 - Injury criterion for anterior-posterior shear force at head-neck junction (Mertz 1984)

Note — Loads are in Newtons.

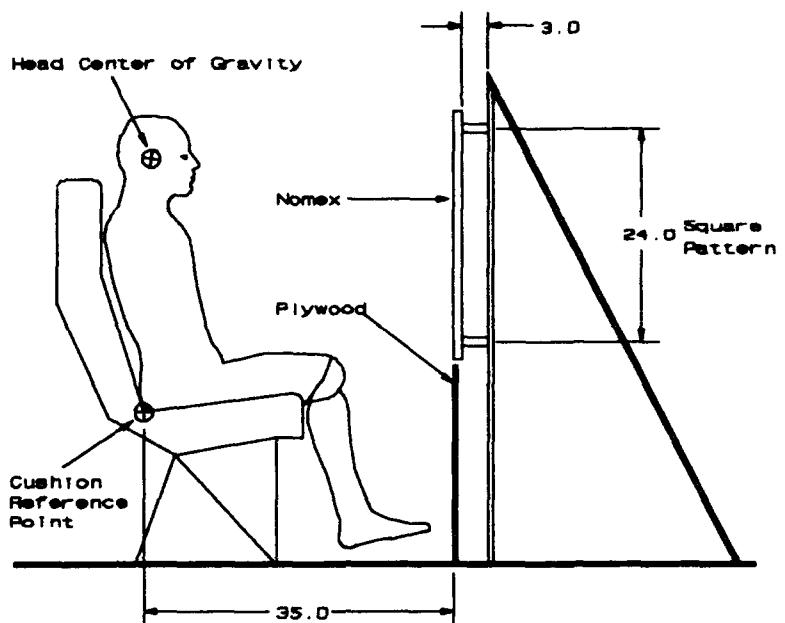
DESCRIPTION OF TESTING PROGRAM

In the interest of protecting the head from injury, the FAA Civil Aeromedical Institute (CAMI) has studied several types of padding materials that could be placed on interior walls (e.g., class divider, galley walls, and lavatory walls) to reduce the HIC level measured during an impact test. However, concern has developed with respect to the effect of these padding materials on neck loads. When the padding is impacted by the head, the padding deforms to the head dimensions. This causes cupping of the head, while the neck and body move with relative freedom. It has been suggested that while padding material may decrease HIC, the loads on the neck may increase to levels causing serious neck injury. In this study, we examine the relationships between padding material, HIC levels, and neck loads.

HEAD STRIKE IMPACT TEST SET UP

Figure 4 - Test Setup for Unpadded Nomex Honeycomb

All dimensions are in inches.



A series of four impact tests were conducted to evaluate HIC and neck loads from a 50th percentile ATD, seated in a transport category aircraft passenger seat positioned behind a vertical wall. The test setup did not model a particular aircraft cabin, but was designed to represent the typical geometry of a seat installation aft of a galley, lavatory, or class divider. Figure 4 shows the test configuration for the "unpadded" Nomex[™] honeycomb test. The "padded" aluminum Hexcel[™] test was similarly configured. A single occupant seat (constructed from components obtained from a three position production model) was used for all four tests. The base of the seat back was located 35 inches aft of the wall plane.

The "unpadded" test used a 1 inch thick panel made of a Nomex[™] honeycomb core and thin fiberglass sheets to simulate a wall in an aircraft. This panel was supported only at the corners allowing it to bend when impacted by the head. The energy absorbing pad used was 4 inch thick aluminum Hexcel[™] with a crush strength of 17 psi mounted on a rigid, unyielding wall. Energy absorption in the padded test occurred by deformation of the Hexcel[™], while in the unpadded test energy was absorbed by the Nomex[™] panel being placed in bending. The wall was not moved relative to the seat between the padded and unpadded tests. Thus, since the Hexcel[™] pad protrudes further from the wall than the unpadded Nomex[™] case, the impact surface is 3 inches closer to the ATD in the padded case.

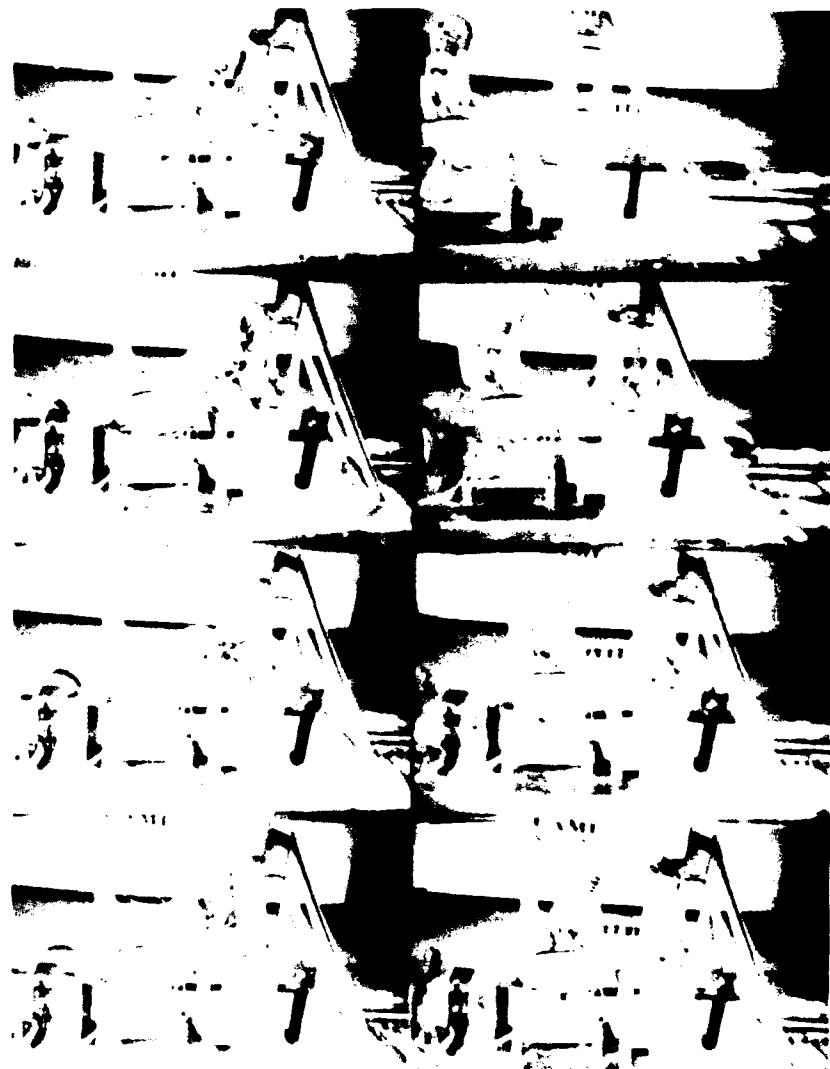


Figure 5 - Selected Frames From High Speed Motion Picture of A92-010 (Hexcel™ Pad)

These tests were conducted in a horizontal-forward orientation with no yaw component (i.e., the ATD faced in the direction that the sled traveled rather than at an angle as specified in the FAR). The severity of impact was selected from the test condition specified in the FARs for transport category aircraft: initial velocity of 44 ft/sec, 16 g peak triangular acceleration pulse, with an onset-to-peak time of 0.090 seconds. Floor deformation was not included in these tests.

In addition to the responses recorded from the sensors mounted in the head and neck of the ATD, photometric targets were placed at selected locations on the test dummy for the purpose of acquiring kinematic data from high speed motion pictures of the impact event. Figures 5 and 6 show selected frames from the high speed motion pictures of the two tests with the Hybrid III. The test films were also useful in relating the motions of the head and neck to the force and moment data acquired from the sensors.



Figure 6 - Selected Frames From High Speed Motion Picture of A92-011 (Nomex™ Panel)

The protocol developed for this program included the use of a Hybrid II and a Hybrid III ATD. The Hybrid II is the ATD specified in the FAR for use in certification tests of aircraft seats, but it lacks the capability to measure neck loads. The newer Hybrid III (currently not allowed for seat certification tests) can accommodate a neck load cell, but there are significant differences in the mass distribution, neck design, and seating posture between the two ATDs. Two tests were performed with each ATD: one test with a rigid wall surface and one test with an energy absorbing pad on the wall.

RESULTS AND DISCUSSION

Table 1 shows the values for HIC and the loads in the neck measured by a Hybrid III ATD used in tests A92010 and A92011, as well as the HIC measured in similar tests using a Hybrid II. The corresponding injury criteria are also presented. Both HIC values are below 1000, with test A92010 giving the lowest HIC value.

Test No.	Impact Surface	Speed (ft/sec)	HIC	Axial Tension (lbs)	Axial Compression (lbs)	Flexion Moment (ft-lbs)	Extension Moment (ft-lbs)	Lateral Flexion Moment (ft-lbs)	Shear (lbs)
Injury Criterion	-----	-----	1000	250 (higher loads for durations < 45 ms)	250 (higher loads for durations < 30 ms)	45	35	29.5	190
A92-010 (Hybrid III)	4" Hexcel* (padded)	44	707	400 (> 250 for 24 ms; 690 allowable)	83	32	43	8	145
A91-119 (Hybrid II)		44	785	NA	NA	NA	NA	NA	NA
A92-011 (Hybrid III)	1" Nomex* (unpadded)	44	901	437 (> 250 for 34 ms; 670 allowable)	388 (>250 for 11 ms; 630 allowable)	19	52	9	151
A91-064 (Hybrid II)		44	1120	NA	NA	NA	NA	NA	NA

* Trade Mark

Table I - Summary of Test Results

NA - Not Available

Neck axial tension was measured, but the maximum value occurred prior to impact, indicating that flailing of the head, rather than head impact, produced the neck axial tension force. Using the short duration neck tension injury criteria indicates that neither test represents a neck tension injury threat.

The axial compression forces and flexion moments for both tests were below the injury threshold. Note that the peaks for both the axial compression force and the flexion moment occurred at the same time. Although it is likely that multiple forces increase the risk of injury, the injury criteria do not take this into account. This phenomenon warrants further study.

The extension moment for test A92010 is 43 ft-lb and corresponds to an AIS = 1 (a whiplash type of injury). The extension moment for test A92011 is 52 ft-lb and corresponds to an AIS = 2. It appears that the 4" Hexcel™ panel not only reduced HIC, but also reduced the neck extension moment.

Neck lateral flexion moments are recorded in Table 1. Although these values are well below the injury threshold, the validity of measuring lateral flexion in the Hybrid III neck is in question. The neck's dynamic performance criteria and compliance properties are based on frontal tests with human subjects, not lateral tests. In addition, it is unlikely that a frontal test with no yaw component would produce any significant forces to place the neck in lateral flexion.

Shear forces measured are below the injury threshold. Shear forces of approximately the same magnitude were generated prior to and after head impact, indicating that head contact did not generate additional shear forces.

Presently, only the Hybrid II test dummy is allowed to be used when evaluating compliance with the FAR. In the present study, we were concerned with HIC values and their relationship to neck loads; therefore, the Hybrid III was employed. Since the Hybrid III and Hybrid II neck differ in their construction and dynamic response, questions have been raised about the effect this has on the measured HIC values. Two separate tests using 4-inch Hexcel™ and 1-inch Nomex™ panels were performed with the Hybrid II, and these test results are shown in Table 1. A HIC of 785 was measured in the Hybrid II test using a 4-inch Hexcel™ panel. This test was performed in the same manner as test A92010 (HIC = 707). HIC values for the Hybrid III test and Hybrid II test are of a similar magnitude. A HIC of 1120 was measured in the Hybrid II test using 1-inch Nomex™; however, the test seat was different than the seat used in test A92011 (HIC = 901). Differences between the seats were minor, but at this time there is no way to fully account for the differences.

CONCLUSIONS

Tests were conducted with a Hybrid III ATD featuring instrumentation in the neck. Measurements made from these instruments are used with the injury criteria presented to analyze the potential for a neck injury resulting from a pad being placed on the interior aircraft wall to reduce the potential for a head injury. Similar tests were run without the pad to demonstrate both the decrease in head injury potential, and the degree to which neck injury potential would be increased, if at all.

Similar tests using a Hybrid II ATD, which does not have neck instrumentation, were also run to evaluate the efficacy of the Hexcel™ pad in reducing HIC. The Hybrid II is the ATD specified for use in certification testing for aircraft, and its design differs in several important respects from the Hybrid III. This testing series found that HIC values measured by the Hybrid III were lower than HIC values measured by the Hybrid II in similar tests.

The tests in general did not indicate a neck injury threat for either case. Indeed, neck injury loads were reduced when the Hexcel™ pad was used. Loads measured and used in the cited injury criteria indicate a neck AIS ≤ 1 , with the exception of the extension moment for test A92011 (the unpadded case), which corresponds to AIS 2.

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